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CRITERIA OF TEMPERATURE CONDITIONS CONTROL IN FIRING OF CERAMIC ARTICLES

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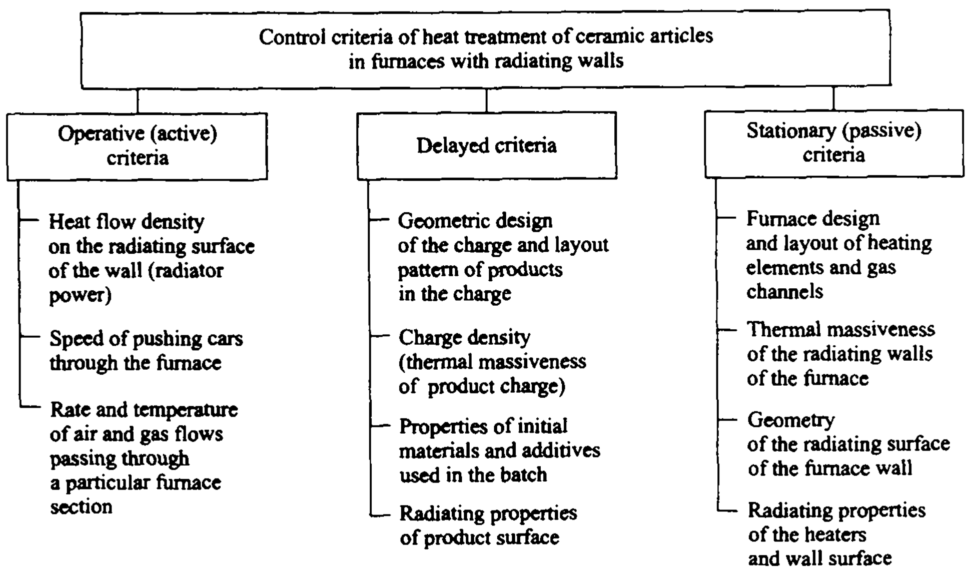
Three groups of criteria of temperature control in firing of ceramic articles are considered. An assessment of the effect of the main control criteria on the firing process is provided for a furnace with radiating walls.

Firing is the most power-consuming process in production of ceramics, and its optimization is closely related to control. The process of firing which forms the physicomechanical properties of the material is complicated by phase transformations and chemical reactions. Technological parameters such as furnace efficiency amount of power supplied to the furnace, air consumed in fuel combustion and chilling of the finished product, quality of the product obtained, and some others are closely related and interdependent. The optimum relationship of these parameters with maximum furnace efficiency and minimum power consumption can be achieved only by providing for properly organized control.

In the course of firing of ceramic articles, most of the heat is transmitted by radiation; therefore, we will analyze the criteria of heat treatment control for furnaces with radiating walls. Three groups of control criteria can be distinguished for these furnaces.



The first group includes criteria of heat treatment control whose modification causes prompt modification of firing condition parameters. These criteria can be termed operative, or active criteria.

The second group includes criteria whose modification brings about modification of heat treatment parameters only after some time has elapsed. This is related to the fact that before firing the products have to pass through the preparation zone for a certain period of time equal to the time lag of the control response. This group of criteria is termed delayed criteria.

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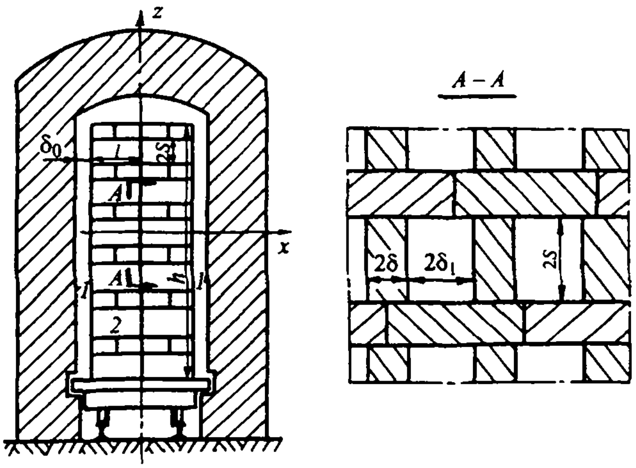

Fig. 1. Lateral section of the furnace firing area: *1*) radiating surface of the wall; *2*) product charge layout.

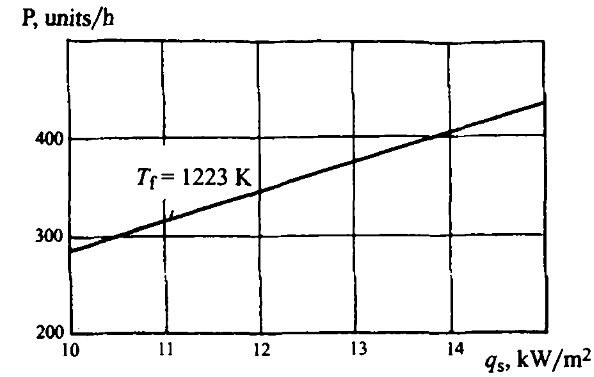

Fig. 3. Dependence of furnace efficiency on heat flow density on the wall radiating surface.

The third group of criteria of heat treatment control can be used only in the stage of developing and designing heat treatment machinery for ceramic articles, since this group consists of structural and heat parameters of the furnace. These control criteria are termed stationary, or passive criteria.

Consider in greater detail the effect of the control criteria on the process of heat treatment of ceramic articles in furnaces with radiating walls.

The electric furnace described in [1] was taken as a prototype (Fig. 1). The charge of products is represented in the form of a high parallelepiped with half-thickness 2l. The charge thickness is significantly smaller than its height and length, therefore heat transfer in the furnace can be reduced to the heat transfer in the elementary cell as was done in [1]. The same paper contains a complete mathematical statement of the heat problem. The solid ceramic bricks fired in the furnace were made of Naumovskoe clay and had the following chemical composition (%): 64.79 SiO_2, 14.40 Al_2O_3, 5.90 Fe_2O_3, 4.23 CaO + MgO, 3.58 K_2O + Na_2O, 7.10 calcination loss.

The thermophysical properties of the clay were determined experimentally and their behavior is described by piecewise linear functions whose values for the nodal points are listed in Table 1. The articles had dimensions of $1 \times 2S \times 2\delta = 260 \times 120 \times 66$ mm and were laid out on the firing car as shown in Fig. 1. The clearances between the vertically placed ceramic items were $2\delta_1 = 66$ mm, which is the optimum value in [2].

Two criteria in the operative criteria group (heat flow density on the radiating wall and the car speed) are interrelated and belong directly to the firing area, i.e., to the area where energy is released by the heat source. The assessment of the effect of these criteria on each other and on the heat transferred to the articles was performed based on mathematical modeling. The following values were used in the calculation in accordance with the designations from [1]: $\rho_c = 0.677$; $d_0 = 0.050$ m; $f_s = 0.0245$ m^2; $f_f = 0.0166$ m^2; $T_0 = 400$ K; $T_s = 700$ K; $\varepsilon_s = 0.75$; $\varepsilon_i = 0.57$; $\alpha_s = 6.3$ W/(m$^2 \cdot$ K); $a_f = 10.8$ W/(m$^2 \cdot$ K); $\alpha_b = \alpha_{gr} = 0$ W/(m$^2 \cdot$ K); $a_1 = 0.02$ W/K; $a_2 = 0$ W/K; $a_3 = q_s f_s$ W; $a_4 = 0.0158$ W/K; $C_s M_s = 26$ J/K; $T_f = 1223$ K.

Fig. 2 reveals the nature of the variation of the furnace brickwork temperature and the average temperature of the product for three values of heat flow density on the radiating wall. Since the speed of pushing the cars through is related to the furnace efficiency, the relationship between the three most important factors (heat flow density on the wall radiating surface q_s , furnace efficiency *E*, and firing temperature T_f) was established (Fig. 3). Knowledge of this relationship enables the furnace operator to modify promptly the level of power supplied to the furnace as a function of the variation in the furnace efficiency and to maintain the firing temperature at the same level. For instance, as the furnace efficiency changes to 200 bricks/hour, the density of the heat flow on the radiating wall surface should be 11.3 kW/m^2.

The majority of the methods currently used in design calculations of firing furnaces use the average values of the thermal parameters of the material fired, and the heat produced by phase transformations and chemical reactions is taken into account as an additional summand in the heat balance equations. For such an appraisal, the average thermal

TABLE 1

Parameter	Thermal properties of Naumovskoe clay at the temperature, °C							
	20	200	330	500	600	680	800	1000
Density, kg/m^3	1970	1970	1970	1950	1870	1800	1870	1950
Specific heat capacity, J/(kg · K)	840	840	3100	1400	1000	1500	800	600
Diffusion coefficient, 10^{-7} m^2/sec	4.23	4.23	1.14	2.56	3.74	2.50	4.68	5.98

parameters of Naumovskoe clay were determined for the temperature range of 293 – 1273 K: density of 1920 kg/m^2, specific heat capacity of 1314 J/(kg · K); diffusion coefficient 2.77×10^{-7} m^2/sec. Fig. 2 shows the nature of variation of the brickwork temperature and average product temperature for $q_s = 12$ kW/m^2 depending on the firing duration. When the behavior of curve *2* is compared to curve *4*, it is apparent that calculation of the firing procedure based on average thermal parameters of the articles can result in serious errors.

The third subgroup of the operative control criteria (flow rate and temperature of air and gas in the furnace) is not considered here, due to the furnace design features, when forced circulation of gas in the firing area is absent.

It is possible to control heat treatment of ceramic articles in the firing area with a certain time lag using the second group of criteria. Modification of the geometric layout of the articles in the charge alters the pattern and intensity of heat transfer to the articles. The duration of heating and firing of articles can be controlled by varying the product charge density. Both control criteria mentioned are most efficient, and they determine the position of the articles on the firing car. An assessment of the effect of these control criteria on heat transfer is given in [2].

Control of the heat treatment process in the firing area can be carried out through modification of the properties of the initial material and the amount of additives. In doing so, the introduction of additives should improve the quality of the product. This particular control criterion can be used for regulating the maximum firing temperature. Above all, the conditions of heat treatment of argillaceous materials are affected by the presence of Al_2O_3, CaO, and MgO which participate in endothermic reactions. The firing calculation analysis carried out for Naumovskoe clay revealed that an increase in the Al_2O_3 content in the clay by 1% produces a decrease in the average product temperature in the firing area by 34 K and a decrease in the furnace wall temperature by 21 K, which results in underfiring of the articles. If the firing temperature and the supply of heat to the furnace remain constant, the furnace efficiency will drop by 2.8%. An increase by 1% in the CaO and MgO content in the initial material causes a drop in furnace efficiency by 3.3 and 3.8%, respectively.

The intensity of radiant heat transfer to the products can be regulated by modification of the radiating properties of the surface of heat-treated articles. Thus, an increase in the radiating capacity of the article surface from 0.57 to 0.617, i.e., by 10%, produces an increase by 6.4% in the furnace efficiency.

The passive criteria of heat treatment control usually are the basis for the development of furnace and heating elements design. Due to modification of the geometric dimensions of the firing channel, air and gas channels, application of different materials and various heating elements (differing in material and design), as well as by application of recirculation, it is possible to develop the conditions for controlling direction and intensity of the radiant heat transfer in the furnace firing channel and thermal massiveness of furnace radiating walls. In the design stage, it is necessary to develop for such furnaces an interior surface radiating layer made of refractory materials with low radiating capacity, since an increase in the furnace wall radiating capacity from 0.75 to 0.825, i.e. by 10%, produces a decrease in furnace efficiency by 7.4%.

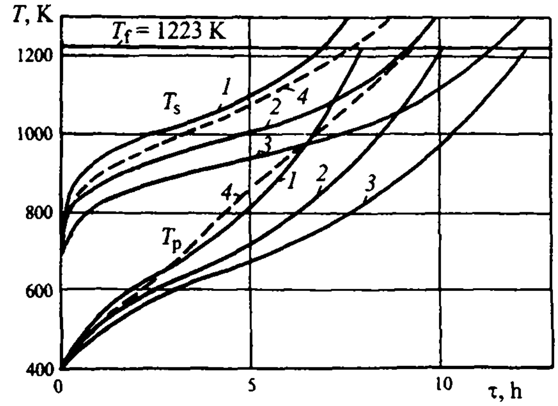

Fig. 2. Modification of the temperature of the furnace wall radiating surface T_s and average product temperature T_p depending on the firing duration: *1*) at $q_s = 15$ kW/m^2; *2*) 12 kW/m^2; *3*) 10 kW/m^2; *4*) at $q = 12$ kW/m^2 and constant average thermal properties of the product material.

The thermal massiveness of furnace radiating walls affects the intensity of heat transfer to the articles making up a charge and the firing duration. Insufficient massiveness of furnace radiating walls requires finer adjustment of the radiating wall temperature $T_s(\tau)$ through the power supplied to the walls, in order to avoid abrupt temperature variations during supply and redistribution of power. Therefore, the materials for refractory and insulating layers used in contemporary firing furnaces are usually fireclay-fiber slabs or refractory fiber materials [3] that virtually do not accumulate heat.

The control criteria for heat treatment of ceramic articles in furnaces with radiating walls considered above are key factors that should be the basis for analysis of functioning furnaces and design of new furnaces for heat treatment of various types of ceramics. There can be only one optimum heat treatment procedure for a particular design and particular efficiency, and this procedure ought to be determined on the basis of the optimization problem that ties together all of the main thermal and technological parameters of ceramic production technology.

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